Compound Semiconductor Devices for Space Applications

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- Material-Interaction induced Failure mechanisms
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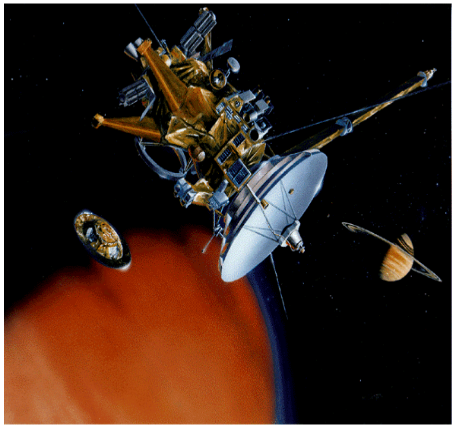
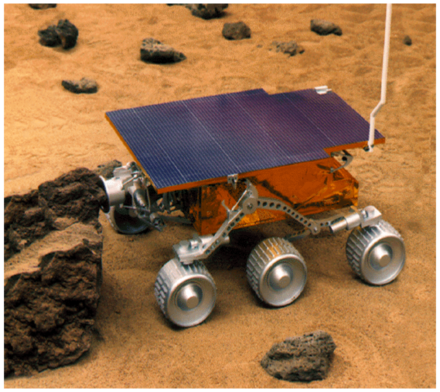
Introduction

- **Space System Applications of Current and Future Missions Require the Use of Highly Advanced Electronic Components in Critical Applications**
- **Devices from Simple Transistors to Complex “System-on-a-Chip” Are Applied Throughout the Spacecraft**
- **The Commercial Focus of the Semiconductor Industry Combined with the Small Market Share of the Space Business Makes the Collection of Reliability Information a more Difficult Task**





Definitions

- **Reliability: "The <u>Probability</u> that an item Will Perform a <u>Required</u> <u>Function</u> Under Stated Conditions for a Stated Period of <u>Time</u>"**
  - **<u>Probability</u>** - Described by Statistical Distribution with Average Parameter and Failure Rate
  - **<u>Required Function</u>** - Defines Failure
  - **<u>Time</u>** - Standard Unit of Measure (Seconds, Revolutions, etc.)
- **Failure: "the act of failing; a falling short; nonperformance; deterioration; bankruptcy"** Webster's Dictionary
- **Failure: "the inability to perform an expected function; the inability to perform a function as expected"** Sammy's Dictionary

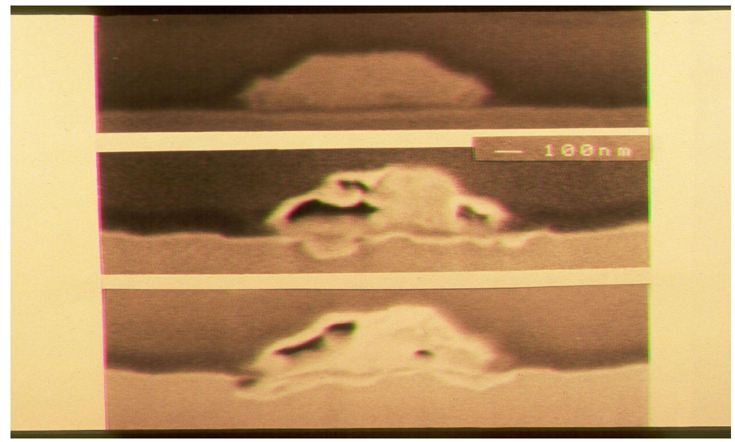
Failure Mechanism Categories

- **Material-Interaction induced Failure mechanisms**
- **Stress Induced Failure Mechanisms**
- **Mechanically Induced Mechanisms**
- **Environmentally Induced Mechanisms**

Material Interaction Induced Mechanisms

Gate Metal Sinking

- Inter-diffusion of gate metal with GaAs resulting in a reduction of the active channel depth and a change in the effective channel doping.
- The process is affected by the surface conditions at the time of deposition, the deposition parameters, and the choice of deposited materials.
- Device electrical parameters such as drain saturation current and reverse breakdown are directly effected by this mechanism.



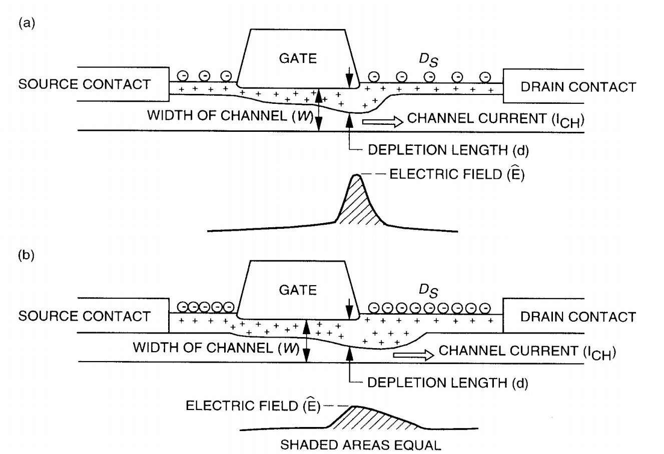
FIB Cross-sections of Control and Two Degraded Gate Locations

Gate Sinking Caused by 4380 hours at 260ºC

Material Interaction Induced Mechanisms

Surface State Effects

- The presence of a high concentration of surface states at the interface between GaAs and metal or the passivation.
- The quality of the interface depends on the surface cleaning materials and procedures, the deposition methods and conditions, and the composition of the passivation layer.
- The mechanism is manifested as an increase in the depletion region and a change in the breakdown voltage.

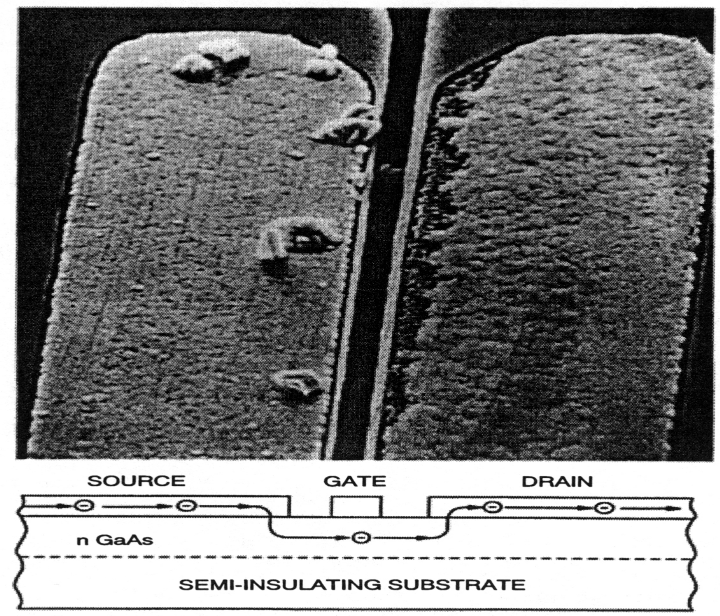


Schematic cross section of a MESFET with Different surface charges. The gate-drain bias is the same for the two cases: (a) with low density of surface states Ds and (b) with high density of Ds

Stress Induced Failure Mechanisms

Electromigration

- The movement of metal atoms along a metallic strip due to momentum exchange with electrons
- Depends on the temperature and the number of electrons
- Generally seen in narrow gates and power devices where the current density is greater than 2×10^5 A/cm^2
- Effect is observed both perpendicular to and along the source and drain contact edges and also at the interconnect of multilevel metallizations.

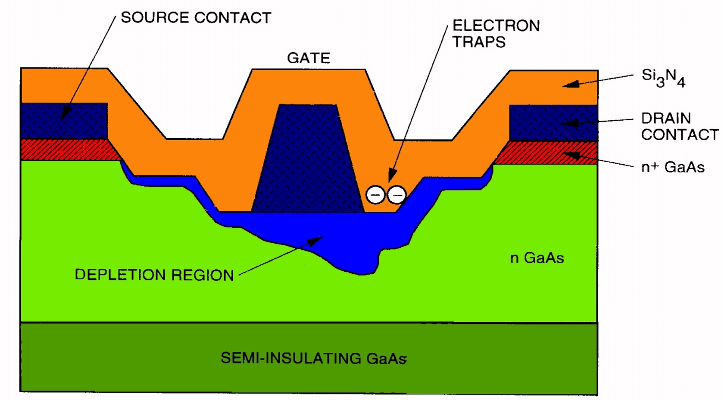


Depletion and accumulation of material in AuGeIn source and drain ohmic contacts induced by electromigration in a low-noise MESFET after life test.

Stress Induced Failure Mechanisms

Hot Electron Trapping

- Under RF Overdrive, hot electrons are generated near the drain end of the channel where the electrical field is the highest.
- Electrons can accumulate sufficient energy to tunnel into Si_3N_4 passivation to form permanent traps.
- The traps can result in lower open-channel drain current and transconductance, and higher knee voltage, leakage current, and breakdown voltage.

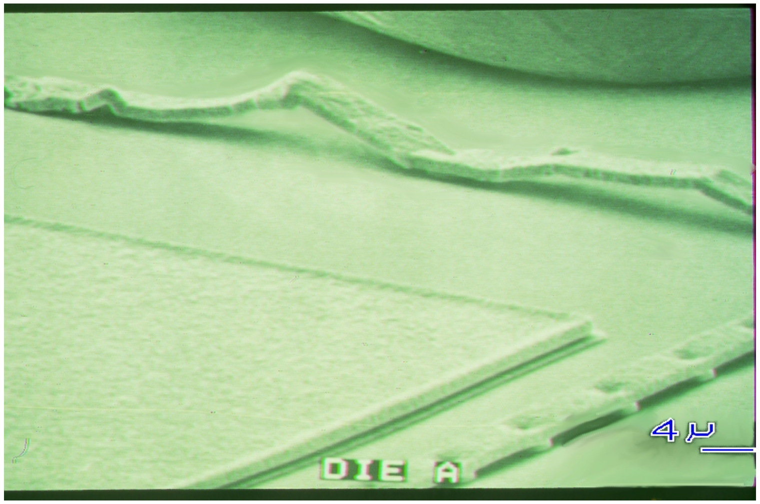


Schematic cross section of a degraded MESFET. Hot-electron-induced traps are formed in the Si3N4 passivation layer between the gate and drain.

Stress Induced Failure Mechanisms

Electrical Stress

- Improper application or use of the device can result in Electrical Over Stress (EOS) failures.
- The discharge of large electrical pulses causing damage to the gate and ohmic metallization structures.
- Results in local melting and pursuant parameter degradation or catastrophic failure.
- Passive elements can also exhibit detrimental effects of electrical overstress.

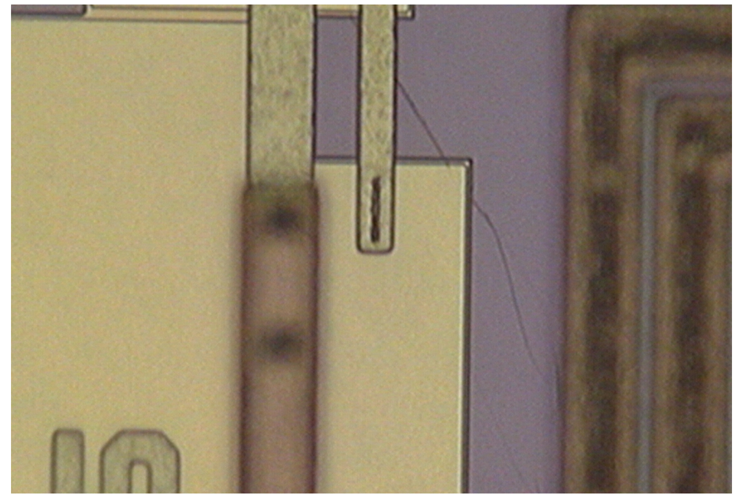


Airbridge Metal Deformation Caused By High Current >4 million A/cm^2, 175ºC, 1000 hours

Mechanically Induced Mechanisms

Die Fracture

- Die surface cracks and fractures at or close to an active region of the device.
- Fractures may result in threshold voltage shifts, increase in leakage current, and other general device performance degradation.
- Can result from differences in Coefficient of Thermal Expansion (CTE) or improper dicing or mounting techniques.

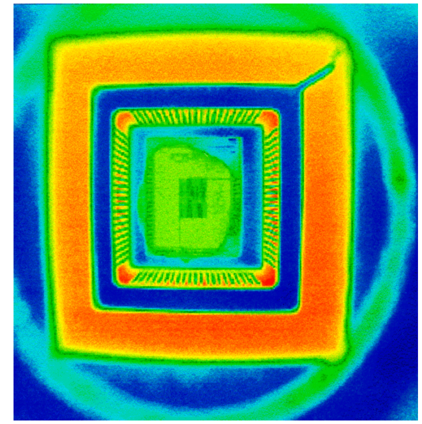


Die Crack Discovered After IR Reflow Simulation

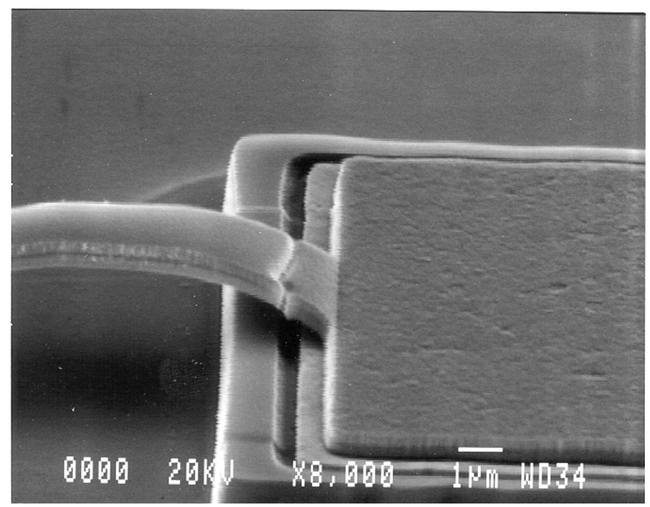
Mechanically Induced Mechanisms

Die Attach Voids

- Presence of voids in die attach materials may result in the formation of hot spots and thermal runaway.
- Propagation of voids may result in die delamination and interruption of the thermal path.
- Physical die detachment from the package of substrate is seldom observed.
- Surface Cleanliness and proper utilization of die attach materials is essential.



Infra-red image of die with voids

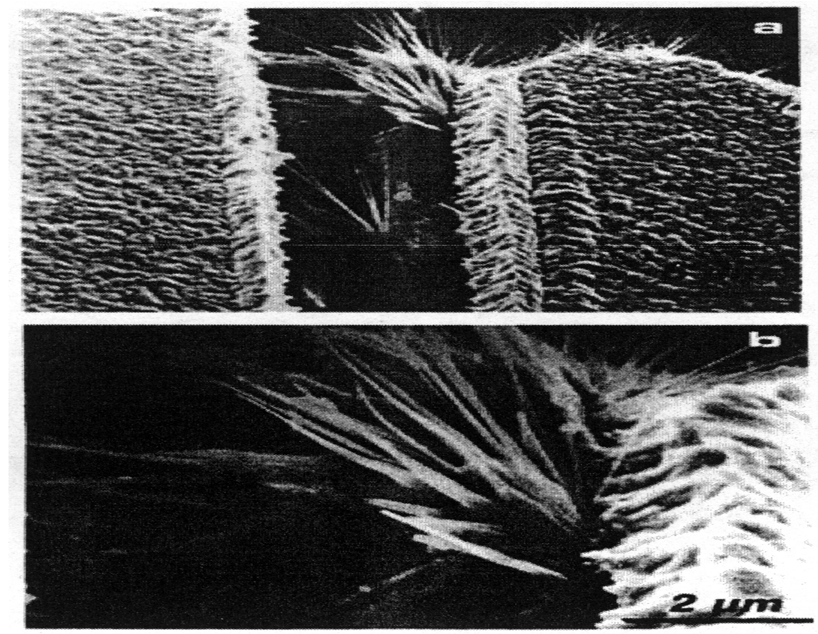


Air Bridge Voids

Environmentally Induced Mechanisms

Humidity Effects

- Ni filamentary growth and Anodic gold corrosion have been observed under high humidity tests
- Formation of gold hydroxide (Au(OH)3) has been detected.
- Effect is theorized to lead to reduction in channel thickness and degradation of device parameters.

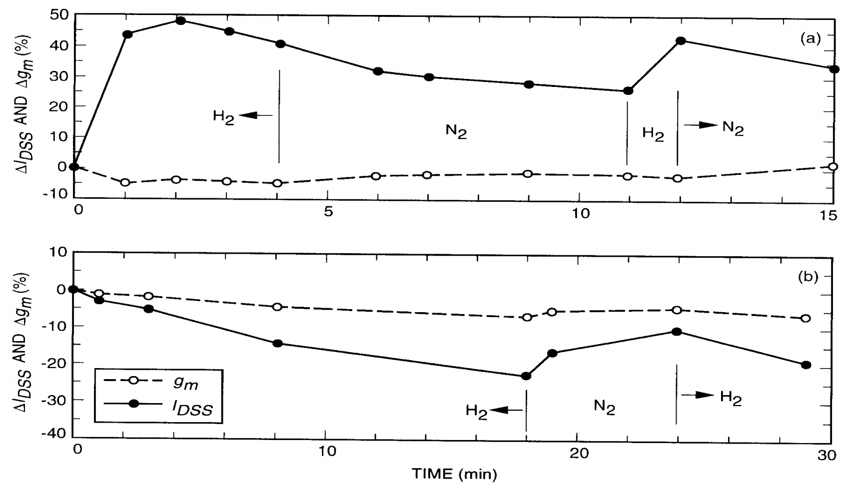


Filamentary growth: (a) nickel extrusion from the AuGeNi ohmic contact of an Au/Pd/Ti low-power MESFET passivated by Si3N4, submitted to an 85% RH/125C HAST test and (b) enlarged view, evidencing dimensions of the whiskers

Environmentally Induced Mechanisms

Hydrogen Effects

- Degradation of device performance in hermetic packages
- Device degradation in I_{DSS}, g_m, gain, other
- Major effects observed on devices with TiPtAu or TiPdAu gate structures.
- Hydrogen getter materials and thermal treatment of the packaging materials have been utilized to minimize the occurrence.

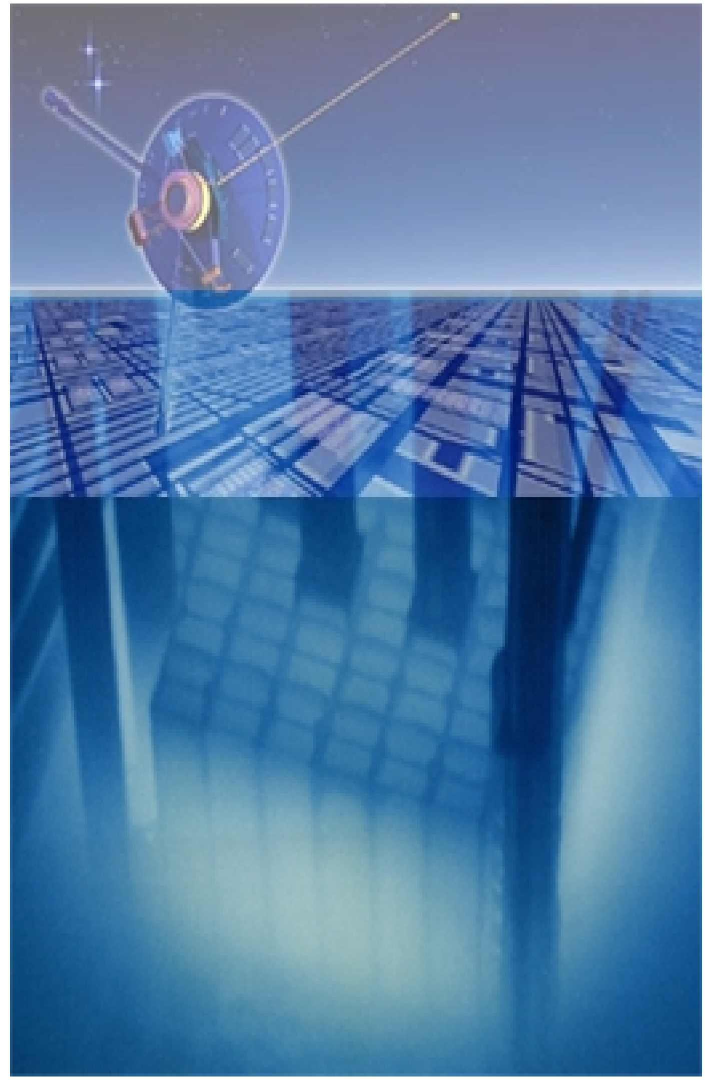


Changes in peak transconductance, g_m, and drain current at zero bias, I_{dss}, of (a) InP HEMT and (b) GaAs PHEMT under nitrogen and 4% hydrogen treatment at 270°C

Environmentally Induced Mechanisms

Radiation Effects

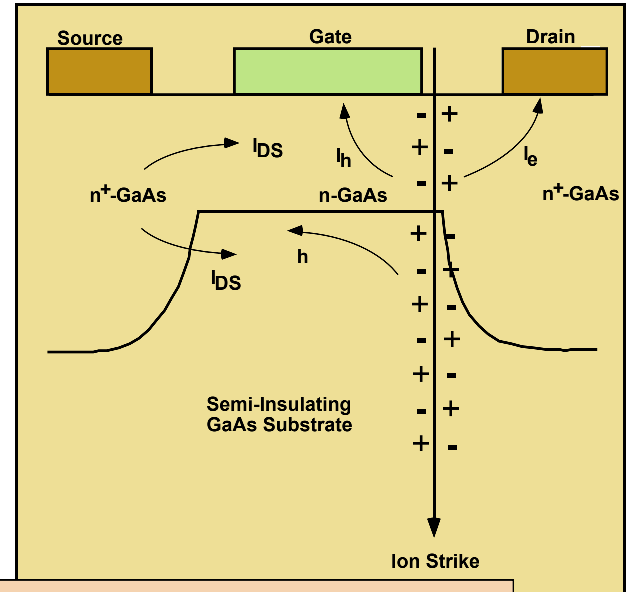
- **Permanent Damage from Protons and Electrons**
  - Most III-V Devices Are Insensitive to Surface Effects (Total Dose)
  - Displacement Damage Is the Critical Problem
    - Requires Tests at Particle Accelerators
  - Single-Event Upset from Proton Reactions and Cosmic Rays Usually the Dominant Issue for III-V Devices
  - Little Testing on Newer Technologies

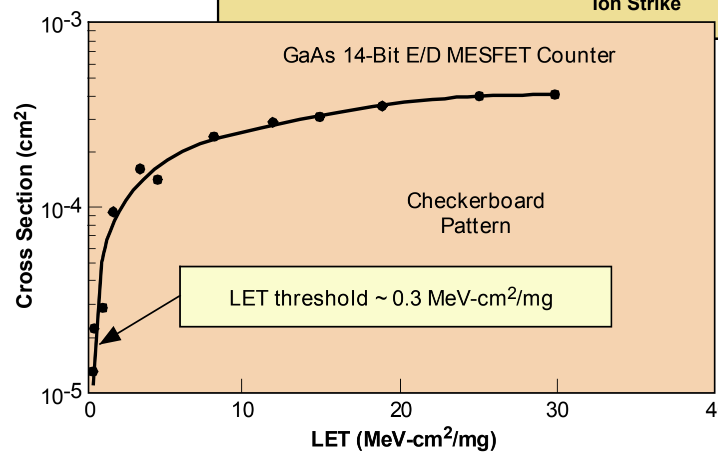


Environmentally Induced Mechanisms

Single-Event Upset in GaAs Devices

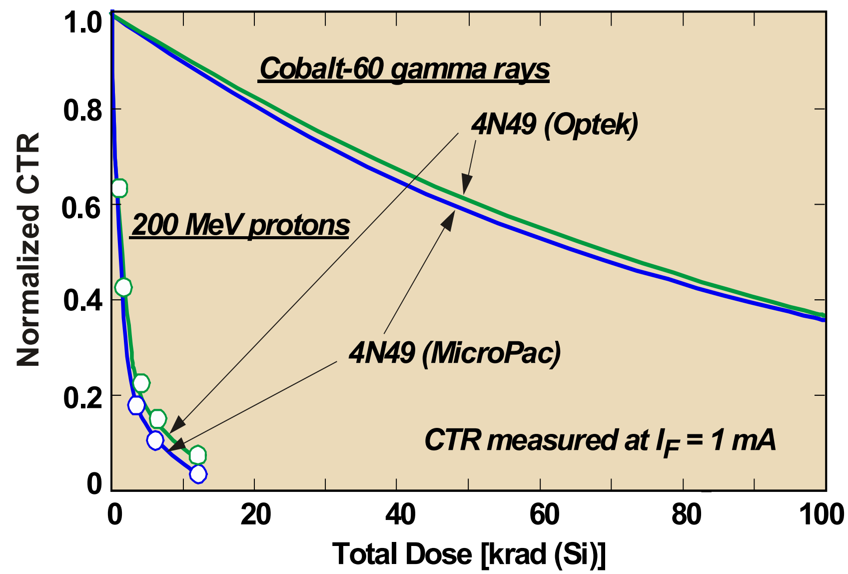
- **High Operating Speed Increases SEE Sensitivity**
  - **Affects Flip-Flops and Other Storage Elements**
  - **Transients in Logic also Important**
  - **Transients Critical in Fiber Optic Receivers**
- **Older Fabrication Methods *Highly* Susceptible**
  - **Charge Persists for Very Long Times in Semi-insulating Substrates**
  - **Extremely Low Threshold LET (~ 2 MeV-cm^2/mg)**
- **HFETs Usually Use Different Substrate Technology**
  - **Significant Improvement Compared to Semi-Insulating Technologies**
  - **High Speed Means that SEU Is Still a Problem**
- **Latchup Has Not Been Observed**
  - **Other Catastrophic Effects Are Possible**
  - **Gate Rupture Effects May Be Possible**





Environmentally Induced Mechanisms

- **Displacement Damage in Light Emitting Diodes**
- **Light-Emitting Diodes Depend on Minority Carriers for Operation**
- **Wide Variation in Fabrication Technologies**
  - **Diffused Process - *wider junctions and increased radiation sensitivity***
  - **Double-Heterojunction Process - *less affected by radiation damage***
- **Some LEDs Are Severely Damaged at Very Low Radiation Levels**
  - **50% Degradation at 1krad Equivalent Total Dose from Protons**
  - **Used in Many Optocouplers**
- **LED Specifications Usually Do Not Specify Fabrication Method**
  - **Major Issue for Use of LEDs and Optocouplers in Space**
  - **Controls and Requirements Needed because of Extreme Sensitivity to Damage**



Summary

- The application of compound semiconductor devices in high reliability systems requires a thorough understanding of the technology's reliability issues and relevant failure mechanisms.
- Advancements in device design and fabrication technology present a constant challenge to understanding reliability in high consequence systems.
- Gaining an adequate understanding of the performance of compound semiconductor devices under a radiation environment is essential for long term reliability and operation.